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Van Loon, Anne

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Overview

Hydrological drought explained

Anne F. Van Loon*

Drought is a complex natural hazard that impacts ecosystems and society in many ways. Many of these impacts are associated with hydrological drought (drought in rivers, lakes, and groundwater). It is, therefore, crucial to understand the development and recovery of hydrological drought. In this review an overview is given of the current state of scientific knowledge of definitions, processes, and quantification of hydrological drought. Special attention is given to the influence of climate and terrestrial properties (geology, land use) on hydrological drought characteristics and the role of storage. Furthermore, the current debate about the use and usefulness of different drought indicators is highlighted and recent advances in drought monitoring and prediction are mentioned. Research on projections of hydrological drought for the future is summarized. This review also briefly touches upon the link of hydrological drought characteristics with impacts and the issues related to drought management. Finally, four challenges for future research on hydrological drought are defined that relate international initiatives such as the Intergovernmental Panel on Climate Change (IPCC) and the 'Panta Rhei' decade of the International Association of Hydrological Sciences (IAHS).

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HYDROLOGICAL DROUGHT IN CONTEXT

Hydrological drought refers to a lack of water in the hydrological system, manifesting itself in abnormally low streamflow in rivers and abnormally low levels in lakes, reservoirs, and groundwater.[1] It is part of the bigger drought phenomenon that denotes a recurrent natural hazard.[2] Societies around the world are exposed to a multitude of natural hazards, such as earthquakes, volcanic eruptions, hurricanes, storms, tornadoes, floods, and droughts.[3,4] Hydrological extremes (floods and hydrological droughts) are natural hazards that are not confined to specific regions, but occur worldwide and, therefore, impact a very large number of people.[5] Flooding events receive most attention, both in the news and in scientific literature, due to their fast, clearly visible, and dramatic consequences. Drought events, also called 'the creeping disaster',[6,7] develop slower and often unnoticed and have diverse and indirect consequences. Hydrological droughts can, however, cover extensive areas and can last for months to years, with devastating impacts on the ecological system and many economic sectors[1,8] (Table 1). Examples of affected sectors are drinking water supply, crop production (irrigation), waterborne transportation, electricity production (hydropower or cooling water), and recreation (water quality) e.g., Refs 1, 6, 8–13. The ecosystem impacts of drought differ between terrestrial ecosystems, in which droughts influence tree mortality due to wild fires,[14,15] and aquatic ecosystems, where they affect e.g., species composition, population density,[16] and food web structure.[17] Examples of drought events in the recent and distant past and their impacts are provided in Box 1.

Currently, there is increasing awareness of drought and related hazards (heat waves and wildfires), resulting in more research on the topic in international projects like WATCH (www.eu-watch.org), DEWFORA (www.dewfora.net), DROUGHT-R&SPI (www.eu-drought.org) and DrIVER (www.drought.uni-freiburg.de), and national projects like DROUGHT-CH (www.nfp61.ch/E/projects/cluster-hydrology/droughts) and four recently started projects in the UK, i.e., MarRIUS, IMPETUS, DRY, and Historic Droughts (www.nerc.ac.uk/research/funded/programmes/droughts). Additionally, there

*Correspondence to: a.f.vanloon@bham.ac.uk

School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, UK

TABLE 1 | Major Impacts of Drought in Relation to the Different Drought Categories

Impact Category		Drought Category Meteorological Drought	Soil Moisture Drought	Hydrological Drought
Agriculture	Rainfed	x	x	
	Irrigated		x	x
Ecosystems	Terrestrial	x	x	
	Aquatic			x
Energy and industry	Hydropower			x
	Cooling water			x
Navigation				x
Drinking water				x
Recreation				x

are increasing efforts to inform policy makers, water managers, and the general public via, for example, the European Drought Centre (EDC; www.geo.uio.no/edc), the US Drought Monitor[18] (www.droughtmonitor.unl.edu), the European Drought Observatory (EDO; edo.jrc.ec.europa.eu), and the Global Integrated Drought Monitoring and Prediction System (GIDMaPS; www.drought.eng.uci.edu).

Recent research projects have significantly increased scientific understanding of the drought phenomenon, its causing mechanisms, its impacts, and changes in time and space. One of the most important scientific developments is the growing view that droughts cannot simply be characterized by a lack of rainfall, and many recent papers show the increased complexity of drought including hydrological processes e.g., Refs 19–21. There are, however, still many uncertainties and gaps in our knowledge about hydrological drought. Mishra and Singh,[7] Cloke and Hannah,[22] and Pozzi et al.[23] argue that hydrological drought deserves more attention due to its crucial link with drought impacts. Also the recent IPCC report on extremes[24] points out the need for more attention to the space–time development of hydrological drought.

In this paper, I therefore aim to give an overview of the state-of-the-art, recent scientific findings, and open questions related to hydrological drought. It aims at students, practitioners, and researchers in various fields. This paper is structured as follows. After a section on the definitions of drought and related phenomena (see section *Drought Definitions*), I go into the processes underlying hydrological drought development and recovery, explaining drought propagation, climate and catchment control, and hydrological drought types and scales (see section *Hydrological Drought Processes*). Then, I discuss methods for drought monitoring, modeling, and prediction

BOX 1

DROUGHT EVENTS

In recent years, many severe drought events occurred. Currently, the state of California in the USA is facing one of the most severe multiyear droughts on record, resulting in extremely low reservoir and groundwater levels and restricting water use for irrigation and domestic use.[25,26] In 2014, a winter drought in Scandinavia caused severe wildfires. In 2013, drought disaster relief was needed in Namibia and Angola, Brazil, central Europe, and New Zealand. In 2012, a simultaneous drought in central and southern USA and Russia induced an increase in food prices. In spring 2011, western Europe faced severe water shortage and low water levels. In 2011, a long-lasting drought triggered hunger, mass migration, and loss of life in the Horn of Africa.[27] In 2010 and 2011, Russia experienced a drought and heat wave,[28] resulting in widespread forest fires.[29] In 2010, large parts of China were affected by drought, hampering food production on a large scale,[30] and in that same year Scandinavia faced drinking water shortage and hydropower production problems.[31] In 2005 and 2010, the Amazon rain forest was affected by a severe lack of precipitation, resulting in a massive dying of vegetation and release of CO_2 into the atmosphere.[32] In 2008, the Iberian peninsula had to cope with the impacts of a multiyear drought that had reduced groundwater levels and reservoir storage to a minimum.[33] A severe continent-wide multiyear drought impacted Australia between 2002 and 2010.[34] In 2003 and 2006, Europe was hit by droughts that caused crop failure, navigation problems, cooling water restrictions, and loss of life due to a heat wave[35] (Figure 1). In 2003, this amounted to 70,000 heat-related deaths in Europe.[36] This enumeration of recent droughts is not exhaustive, but indicates the recurring and worldwide nature of droughts.

Contrary to expectation (a common misconception is that drought impacts on society are limited to semiarid regions), droughts in wet and cold regions can result in major damage. Examples are problems with electricity production and drinking water supply in Scandinavia e.g., Ref 31 and livestock mortality and economic loss in regions like Mongolia.[37,38] It is not a coincidence that people in Mongolia have a local name for drought related to extremely low temperatures, namely 'Dzud',[39] and that special aid programs exist for Mongolia because this type of drought generally causes serious loss of livestock.[40,41]

Drought is not a recent phenomenon. Actually, some of the most devastating drought events occurred in the previous century. Examples are the 1976 drought in Europe, the 1930s Dust Bowl in the USA,[42] and the 1920s food crisis in Russia and China (in which more than 4 million people died, EM-DAT[43]). The wider drought phenomenon is considered one of the most damaging natural hazards in terms of economic cost[6] and, regionally, in terms of societal problems, such as hunger, mass migration, and loss of life. In the period 1900–2010, worldwide two billion people were affected and more than 10 million people died due to the impacts of drought.[43,44]

Also in the paleoclimatic record, many severe 'mega-droughts' are reported that had widespread ecological and socioeconomic consequences and might even be related to the collapse of civilisations e.g., Refs 8, 24, 45–48.

(see section *Hydrological Drought Quantification*). I briefly mention research on drought impacts and management (see section *Hydrological Drought Impacts and Management*), before going into defining some challenges for the future (see section *Challenges for Hydrological Drought Research*) and giving some concluding remarks (see section *Concluding Remarks*).

DROUGHT DEFINITIONS

Drought is a complex phenomenon and is therefore defined in many ways. No universal definition of drought exists.[49] Reviews of definitions can be found in Dracup et al.,[50] Wilhite and Glantz,[2] Hisdal,[51] Tallaksen and Van Lanen,[1] Mishra and Singh,[7] and Sheffield and Wood.[8] The most simple definition of drought is: a deficit of water compared with normal conditions.[8] In applying this definition, the following questions arise. What are normal conditions? Do we consider water in all components of the hydrological cycle or only in some? How large must a water deficit be, or how long is it to last, in order to be called a drought? Does this definition only refer to natural processes or do human influences play a role as well?

What should be regarded as the 'normal' situation strongly depends on what the water is used for. For example, certain minimal water levels in rivers are needed for navigation and ecosystems, whereas in reservoir management deviations from the seasonal inflow cycle have serious impacts. Hence, the definition of drought is dependent on the objective of a study, which is very important when quantifying drought.[49] In drought research, we generally focus on the atmospheric and terrestrial components of the water cycle and the linkages between them, i.e., precipitation, evapotranspiration, snow accumulation, soil moisture, groundwater, lakes and wetlands, and streamflow.[8] Furthermore, it is customary to define drought as a persistent and regionally extensive phenomenon, although these terms are not easily quantified. It is also important to note that drought is a relative, rather than absolute, condition of the hydrological system.[52]

In this paper, I use the following definition of drought, proposed by Tallaksen and Van Lanen[1]:

> Drought is a sustained period of below-normal water availability. It is a recurring and worldwide phenomenon, with spatial and temporal characteristics that vary significantly from one region to another.

Droughts are generally classified into four categories e.g., Ref 1, 2, 7, 8, visualized in Figure 2:

1. Meteorological drought refers to a precipitation deficiency, possibly combined with increased potential evapotranspiration, extending over a large area and spanning an extensive period of time.
2. Soil moisture drought is a deficit of soil moisture (mostly in the root zone), reducing the supply of moisture to vegetation. Soil moisture drought is also called agricultural drought, because it is strongly linked to crop failure. As soil moisture deficits have additional impacts on, for example, natural ecosystems and infrastructure,[24,56,57] I

FIGURE 1 | Examples of impacts of the 2003 summer drought in Europe, including effects on agriculture, health, transport, energy, and ecology. (Figure by A.J. Teuling, Wageningen University)

do not use the term agricultural drought for soil moisture drought in this paper.

3. Hydrological drought is a broad term related to negative anomalies in surface and subsurface water. Examples are below-normal groundwater levels or water levels in lakes, declining wetland area, and decreased river discharge. Groundwater drought and streamflow drought are sometimes defined separately as below-normal groundwater levels[7,53,58,59] and below-normal river discharge,[60–63] respectively.
4. Socioeconomic drought is associated with the impacts of the three above-mentioned types. It can refer to a failure of water resources systems to meet water demands and to ecological or health-related impacts of drought. An overview of the most important drought impacts is provided in Table 1. It can be noted that more types of drought impacts are related to hydrological drought than to meteorological drought.

Drought should not be confused with low flow, aridity, water scarcity, or desertification, or with related hazards such as heat waves and forest fires. 'Low flow' is a frequently used term, denoting low river discharge.[61,64,65] Low flows are often characterized by annual minimum series, which do not in all years reflect a streamflow drought. Hence, Hisdal et al.[58] propose to distinguish between low flow characteristics and streamflow drought characteristics. 'Aridity' is the general characteristic of an arid climate and represents a (relatively) permanent condition, while drought is temporary.[7] In an arid climate, drought can still occur when local conditions are even drier than normal.[8,66] The term 'water scarcity' is used to denote a water supply shortage or a situation in which anthropogenic influence on the water system plays an important role in the development of below-normal water availability. Water scarcity is caused fully or in part by human activities[24] and reflects conditions with long-term imbalances between available water resources and demands e.g., Ref 1, 67. Water scarcity and drought are usually hard to distinguish as they are closely linked and often occur simultaneously. Van Loon and Van Lanen[68] used an observation-modeling framework to distinguish between drought and water scarcity. Probably the worst situation with regard to water

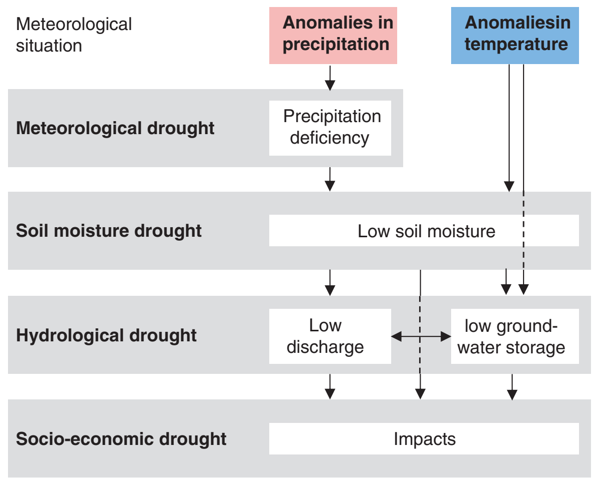

FIGURE 2 | Scheme representing different categories of drought and their development. (Derived from Peters,[53] Van Loon,[54] Stahl[55]).

management is a drought in the low-flow season in an arid climate that additionally suffers from water scarcity.

The term ‘desertification’ is related to misuse or mismanagement of a region with a dry climate, leading to a reduction in vegetation cover.[69,70] Dry periods can intensify desertification. ‘Heat waves’ develop as a result of high temperatures. Soil moisture drought can aggravate heat waves, due to feedbacks of the land surface with the atmosphere.[71–74] The typical time scale of heat waves is in the order of weeks, whereas drought generally has durations of months to years.[7] ‘Forest fires’ are uncontrolled fires in a wooded area. The risk of forest fire appears to increase with drought,[75] although in some regions human activities were found to be the most important driving force for forest fires.[76]

If hydrological drought is framed as a natural hazard, terms for the hazard literature are often used, e.g., ‘disaster’ for its negative impacts on society and the environment,[52] and ‘vulnerability’ to denote the lack of capacity to cope with the ‘risk’ of drought.[77,78] Alternatively, hydrological drought can be viewed as a water resources issue, with emphasis on the imbalance between water availability and demand e.g., Ref 79. This view incorporates societal and ecological aspects into the phenomenon. It also makes hydrological drought less an external hazard, and more a normal part of the hydrological system.

HYDROLOGICAL DROUGHT PROCESSES

There are a multitude of relevant processes underlying the development and also the recovery of hydrological drought. In this section, an overview is provided of the current knowledge of these processes.

Drought Propagation

Reasons for the occurrence of hydrological drought are complex, because they are dependent not only on the atmosphere, but also on the hydrological processes that feed moisture to the atmosphere and cause storage of water and runoff to streams.[7]

The atmospheric processes that are the starting point of hydrological drought development are a result of climatic variability.[8,66] Generally, a prolonged precipitation deficiency generates less input to the hydrological system (Figure 3). Causative mechanisms of precipitation deficits can be blocking high-pressure systems[81,82] and monsoon failure.[83,84] Alternatively, hydrological drought can be triggered by anomalies in temperature, such as prolonged freezing conditions in winter in snow-dominated catchments[85] or low temperatures in summer in glacier-dominated catchments.[86] Both temperature and precipitation anomalies can be associated with large-scale atmospheric or ocean patterns like ENSO, NAO, and sea surface temperatures e.g., Ref 87, 88.

Depletion of soil moisture storage is related to its antecedent condition, evaporation from bare soil, evapotranspiration through plants, drainage to the groundwater, and runoff to streams. During a dry spell, drainage and runoff are usually low, but potential evapotranspiration can increase due to increased radiation, wind speed, or vapor pressure deficit (e.g., caused by a decreased moisture availability or an increased temperature). This can lead to increased actual evapotranspiration, resulting in an extra loss of water from the soil and open water bodies. In extreme drought, a lack of available soil moisture and wilting of plants can limit evapotranspiration, thus limiting a further soil moisture depletion, but possibly also limiting locally generated precipitation, contributing to the maintenance of drought conditions. Vegetation is an important factor in modifying these feedbacks. Examples with evidence for strong feedbacks are given in D’Odorico and Porporato,[89] Teuling et al.,[90] Bierkens and van den Hurk,[91] Dekker et al.,[92] Ivanov et al.,[93] and Seneviratne et al.[94]

The depletion of soil moisture storage causes a decreased recharge to the groundwater system, resulting in declining groundwater levels. Actual groundwater levels are dependent on the pre-event conditions and the rate of decline, which again depends on the amount of recharge and discharge and the storage characteristics of the aquifer. Since

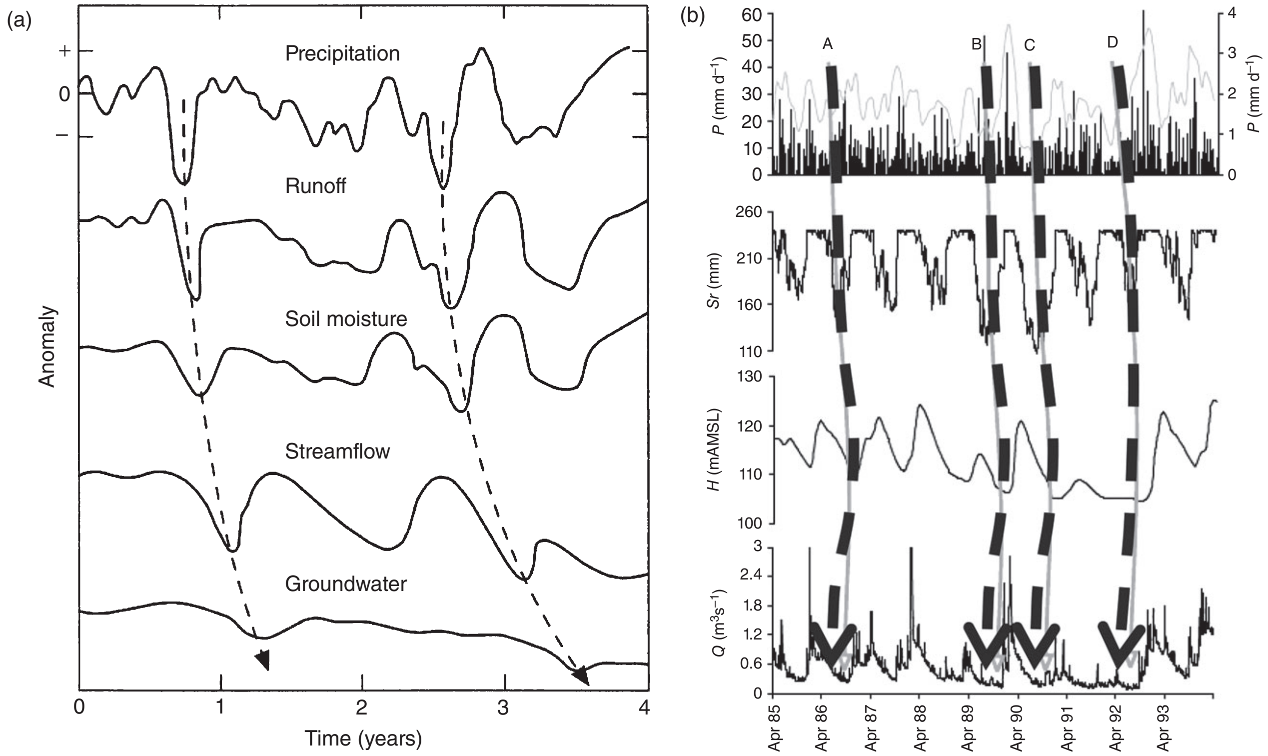

FIGURE 3 | Propagation of a precipitation anomaly through the terrestrial part of the hydrological cycle for various variables, (a) synthetic time series[80]: 0, mean, +, positive anomaly, −, negative anomaly, (b) time series of the Pang catchment[53] (UK): P, precipitation, Sr, soil moisture storage in the root zone, H, groundwater level, and Q, streamflow. Propagation of drought events is indicated by the arrows. Note that the order of the variables is different in (a) and (b).

the reaction of groundwater to climatic input is often delayed and smoothed, a groundwater drought does not always develop, but when it does it often shows long periods of below-normal groundwater levels. As discharge is strongly linked to storage, low groundwater levels lead to decreased groundwater discharge, which slows down the drying process of the aquifer, but also causes decreased streamflow e.g., Ref 95. During drought the main contribution to discharge is via these slow pathways of groundwater discharge (baseflow). The fast pathways that contribute to discharge during wetter periods (surface runoff, interflow) are usually limited during drought. This chain of processes is summarized with the term ‘drought propagation’, which denotes the change of the drought signal as it moves through the terrestrial part of the hydrological cycle.

The relationship between precipitation, soil moisture, runoff, recharge, groundwater, and discharge is an old concept in hydrology, but the application of this knowledge to drought is relatively recent. The first research addressing changes in the drought signal due to propagation through the hydrological cycle was done in Illinois, USA, by Changnon Jr[80] and Eltahir and Yeh.[96] The latter were the first to use the word ‘propagation’ in the context of the translation from meteorological to hydrological drought. This work[80,96] was continued by Peters[53] who published a study on the propagation of drought in groundwater. In recent years, drought propagation has been studied by, among others, Tallaksen and Van Lanen,[1] Peters et al.,[59] Van Lanen,[97] Tallaksen et al.,[98] Tallaksen et al.,[99] Di Domenico et al.,[100] Vidal et al.,[101] and Van Loon.[54]

Note that in the climate community the term ‘drought propagation’ is sometimes used for the spatial migration of a drought event, due to atmospheric transport of anomalously warm and dry air.[102] For example, in eastern China and western USA, a southward migration of meteorological drought was found[103] and in Europe, droughts starting in southern Europe were found to spread northwards.[73,104] In this paper, I use the term ‘drought propagation’ strictly for the translation from anomalous meteorological conditions to hydrological drought.

Figure 3 shows the propagation of drought by means of (1) synthetic time series of anomalies in different hydrometeorological variables by Changnon Jr,[80] and (2) a real-world example from the Pang catchment (UK) by Peters.[53] The general differences between the variables (in both Figure 3(a) and (b)) are: many anomalies in precipitation, fewer and smaller anomalies in soil moisture, and fewer and longer anomalies in groundwater. Streamflow occupies an intermediate position in this sequence, because it is a composite of fast (direct runoff and interflow) and slow (baseflow) flow routes within a catchment. The relative position of streamflow in relation to soil moisture and groundwater is different for different areas, i.e., if a river is mainly discharging groundwater (like the Pang catchment) the streamflow drought signal is comparable to the groundwater drought signal. In Figure 3(a), it should also be noted that the hydrological drought of year 1 is followed by a long period with sufficient recharge to let the system recover to its original state, whereas the drought in year 3 is not compensated by sufficient recharge to assure a complete recovery of the system. The positive precipitation anomaly after the drought in year 3 is almost completely used to recover soil moisture levels and little remains for recovering streamflow and groundwater levels. If the system does not recover before the next meteorological drought develops it turns into a multiyear drought, as is apparent in the groundwater signal. This is also visible in the time series of the Pang catchment (drought C and D in Figure 3(b)).

Propagation of drought is characterized by a number of features,[95,96,105] which are related to the fact that the terrestrial part of the hydrological cycle acts as a low-pass filter to the meteorological forcing.[106–108] Here, they are shortly summarized and visualized in Figure 4.

- Pooling: meteorological droughts are combined into a prolonged hydrological drought.
- Attenuation: meteorological droughts are attenuated in the stores, causing a smoothing of the maximum negative anomaly.
- Lag: a lag occurs between meteorological, soil moisture, and hydrological drought, i.e., the timing of the onset is later when moving through the hydrological cycle.
- Lengthening: droughts last longer when moving from meteorological drought via soil moisture drought to hydrological drought.

These features are controlled by catchment characteristics and climate. Lag and attenuation are governed by catchment control, and pooling and lengthening by both catchment control and climate control.[95,54]

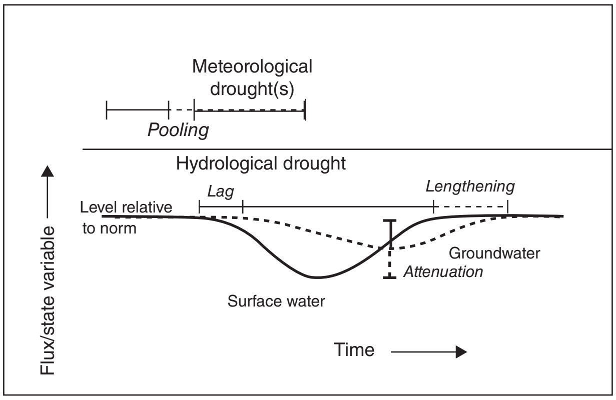

FIGURE 4 | Features characterizing the propagation of meteorological drought(s) to hydrological drought: pooling, lag, attenuation, and lengthening. (Reprinted with permission from Hisdal and Tallaksen[109])

Climate Control on Hydrological Drought

Drought propagation is dependent on climate.[8] Various authors examined the dependency of drought characteristics on climate. In Stahl and Hisdal[66] a broad overview is given of hydroclimatological regimes and potential for drought development in different climates around the world. Recent global-scale studies on the effect of climate on hydrological drought are for example Van Lanen et al.[110] and Van Loon et al.[111]

In general, hydrological droughts develop differently in relatively constant climates as compared with climates with strong seasonality. In a constant climate, the main factor for drought development is a below-normal precipitation (possibly combined with higher than normal potential evapotranspiration), as described in section *Drought Propagation*. In a seasonal climate, additional processes lead to the development of summer or winter droughts. In warm seasonal climates, most recharge occurs in a distinct wet season. A drought in this wet season decreases storage and can influence dry-season conditions. During the dry season, potential evapotranspiration is generally higher than precipitation, which potentially gives evapotranspiration a larger role in drought development. This type of hydrological drought is termed *wet-to-dry-season drought* in Van Loon and Van Lanen[85] (see Table 2) and was found to occur predominantly in Mediterranean, savannah, and monsoonal climates.[111]

The role of evapotranspiration, however, is still highly uncertain. For example, Kriaučiuniene et al.[112] found that in Lithuanian rivers (based on data starting in 1810) precipitation was more important than temperature (reflecting evapotranspiration) for the timing of dry periods in summer. Teuling et al.,[19] however,

TABLE 2 | Drought Propagation Processes (Including Development and Recovery) per Hydrological Drought Type and Subtype (based on Van Loon and Van Lanen[85] and Van Loon et al.[86])

Hydrological Drought Type	Governing Process(es)	Development	(Lack of) Recovery
Classical rainfall deficit drought	Rainfall deficit (in any season)	*P* control	*P* control
Rain-to-snow-season drought	Rainfall deficit in rain season, drought continues into snow season	*P* control	*T* control
Wet-to-dry-season drought	Rainfall deficit in wet season, drought continues into dry season	*P* control	*P* and *T* control
Cold snow season drought	Low temperature in snow season, leading to:		
Subtype A	Early beginning of snow season	*T* control	*T* control
Subtype B	Delayed snow melt	*T* control	*T* control
Subtype C	No recharge	*T* control	*T* control
Warm snow season drought	High temperature in snow season, leading to:		
Subtype A	Early snow melt	*T* control	*P* control
Subtype B	In combination with rainfall deficit, no recharge	*P* and *T* control	*P* control
Snowmelt drought	Lack of snowmelt in spring due to low *P* or high *T* in winter	*P* and/or *T* control	*P* control
Glaciermelt drought	Lack of glaciermelt in summer due to low *T* in summer	*T* control	*P* or *T* control
Composite drought	Combination of a number of drought events over various seasons	*P* and/or *T* control	*P* control

P, precipitation; *T*, temperature.

argue in favor of a large contribution of anomalies in evapotranspiration to anomalies in storage, based on observational evidence from central and western European catchments.

In seasonal climates with below-zero temperatures and snow accumulation in winter, snow-related processes play a role in drought development. Snow accumulation and frozen soils cause storage of water and prevent recharge to the groundwater, resulting in decreasing groundwater levels and streamflow throughout the winter. Early or late snow melt influences hydrological processes, namely the timing of recharge and discharge to streams.[8,113] Barnett et al.[114] and Van Loon et al.[86] found that not only the timing of the snowmelt (or glaciermelt) is important, but also the amount. A lack of snow or glaciermelt can cause water deficiencies in the high flow season. Frozen soils have a dual effect on drought development. On the one hand they immobilize water in the winter season, but on the other hand they can cause a fast direct runoff when snow melt and rainfall during the (early) melting period cannot infiltrate into the soil. This then leads to less recharge to the groundwater system, which can eventually enhance a summer drought in groundwater. However, many studies indicate that the effect of soil frost enhancing surface runoff during snow melt is limited, at least in forested catchments.[115–117]

In monsoon climates, dry and wet seasons alternate, due to large-scale atmospheric processes. As this is the normal situation in these climates, such a dry season is normally not defined as a ‘drought’ (see section *Drought Definitions*). A drought occurs when the onset of the monsoon is delayed or a complete or partial failure of the monsoon takes place.[84,118] This results in a lack of soil moisture replenishment and recharge after the dry season, causing storage to decrease to below-normal levels.

In arid climates, dry periods are irregular and can last long due to erratic precipitation. Streamflow in these climates is highly dependent on groundwater discharge, showing a long recession during periods without rain.[66] These differences in processes underlying drought development in different climates pose challenges to drought quantification, which are discussed in section *Hydrological Drought Quantification*.

Catchment Control on Hydrological Drought

According to Van Lanen et al.[110] catchment control is as important for hydrological drought as climate control. The propagation of a drought in a fast responding catchment differs from that in a slow responding catchment, i.e., pooling, lag, attenuation, and lengthening of the drought signal are influenced by the catchment characteristics. Not only the hydrological variables discharge and groundwater levels themselves are related to catchment characteristics e.g., Refs 119–122, but also the dry anomalies of these variables, i.e., low flow and drought, as has been shown in many studies. For instance, Keyantash and Dracup[123] related drought severity to surface-water storage, Engeland et al.[124] determined regression equations between low-flow indices and catchment characteristics, Tokarczyk and Jakubowski[125] concluded that different types of rock result in a different development of low flow. Eng and Milly[126] evaluated from previous studies which catchment parameters show a significant relation with low-flow characteristics and found that catchment area and soil type are important. Van Lanen et al.[95] provide a comprehensive overview of the mechanisms by which hydrological processes and catchment characteristics influence hydrological drought. Smakhtin,[61] Demuth and Young,[127] and Laaha et al.[65] do the same for low flows, showing the relationship between low-flow indices and catchment characteristics.

When the response time of a catchment is very long, lag times between meteorological and hydrological drought are very long as well, which can cause a hydrological drought to occur in a different season than the meteorological drought that is causing it. A lack of recharge in winter can then be an important factor in causing a hydrological drought in summer in some slow responding catchments. Peters et al.,[59] for example, found that in a specific groundwater-fed catchment in the UK a sequence of dry winters resulted in a multiyear drought. Marsh et al.,[128] Parry et al.[129] and Kendon et al.[130] put that study in a longer term and wider spatial perspective by showing that multiyear droughts due to a number of dry winters in a row are recurrent in northwestern Europe. Multiyear droughts are also called *composite droughts* by Van Loon and Van Lanen,[85] because drought events with different causing mechanisms are combined. Parry et al.[129] investigated characteristics, spatiotemporal evolution, and synoptic climate drivers of multiyear drought events in Europe and found considerable differences between the events.

For hydrological drought development, the most important catchment characteristic is the storage capacity of a catchment. Major stores in a catchment are: snow and glaciers, peat swamps and bogs, the soil column (in particular when groundwater levels are low), the groundwater system, and lakes and reservoirs. These stores create a long memory in the hydrological system, which determines the transformation of the drought signal.[95,131] In general, storage in a catchment is determined by factors such as the climate (in case of snow and glaciers) and the geology of the catchment (i.e., percentage of hard rock and types of rock), topography, soil (e.g., soil texture and structure), drainage network, land use, and vegetation. Van Loon and Laaha[132] showed that none of these factors is dominant in explaining streamflow drought severity. Only the combination of a large number of storage factors could explain variability in drought duration in a large number of catchments in Austria.[132]

Aquifers are the dominant source of water storage in many regions around the world.[133,134] Aquifer characteristics, therefore, have a strong influence on hydrological drought development and recovery.[135] Stoelzle et al.,[21] for example, found that in Germany karstic and fractured aquifers have a short-term sensitivity to drought, whereas porous and complex aquifers have a more long-term sensitivity to drought. In porous and complex aquifers drought propagation is more catchment-controlled than in karstic and fractured aquifers.[21] For the UK, similar results were found by Bloomfield and Marchant[135]: in fractured aquifers (e.g., chalk) groundwater drought characteristics were determined by the recharge time series, whereas in granular aquifers (e.g., sandstones) intrinsic saturated flow and storage properties of the aquifer were dominant.

Not all catchment characteristics are constant, some change over time e.g., Ref 136. Some change over geological time scales, some change on an interannual of intraannual time scale (like a seasonal snow cover), and some change within a drought event. Eltahir and Yeh,[96] for example, found that drainage density is dependent on groundwater level and thus on the drought state of the system. This nonlinear behavior of storage factors results in an asymmetric response of streamflow to a drought signal.[91,96,137]

Hydrological Drought Types

Parallel to the flood types of Merz and Bloschl,[138] classifying floods into long-rain floods, short-rain floods, flash floods, rain-on-snow floods, and snowmelt floods, Van Loon and Van Lanen[85] and Van Loon et al.[86] developed a hydrological drought typology. They classified hydrological droughts based on their causing factors and propagation processes into *classical rainfall deficit drought*, *rain-to-snow-season drought*, *wet-to-dry-season drought*, *cold snow season drought*, *warm snow season drought*, *snowmelt drought*, *glaciermelt drought*, and *composite drought*. Table 2 summarizes the underlying processes for each hydrological drought type, related to precipitation (*P* control), temperature (*T* control), or a combination

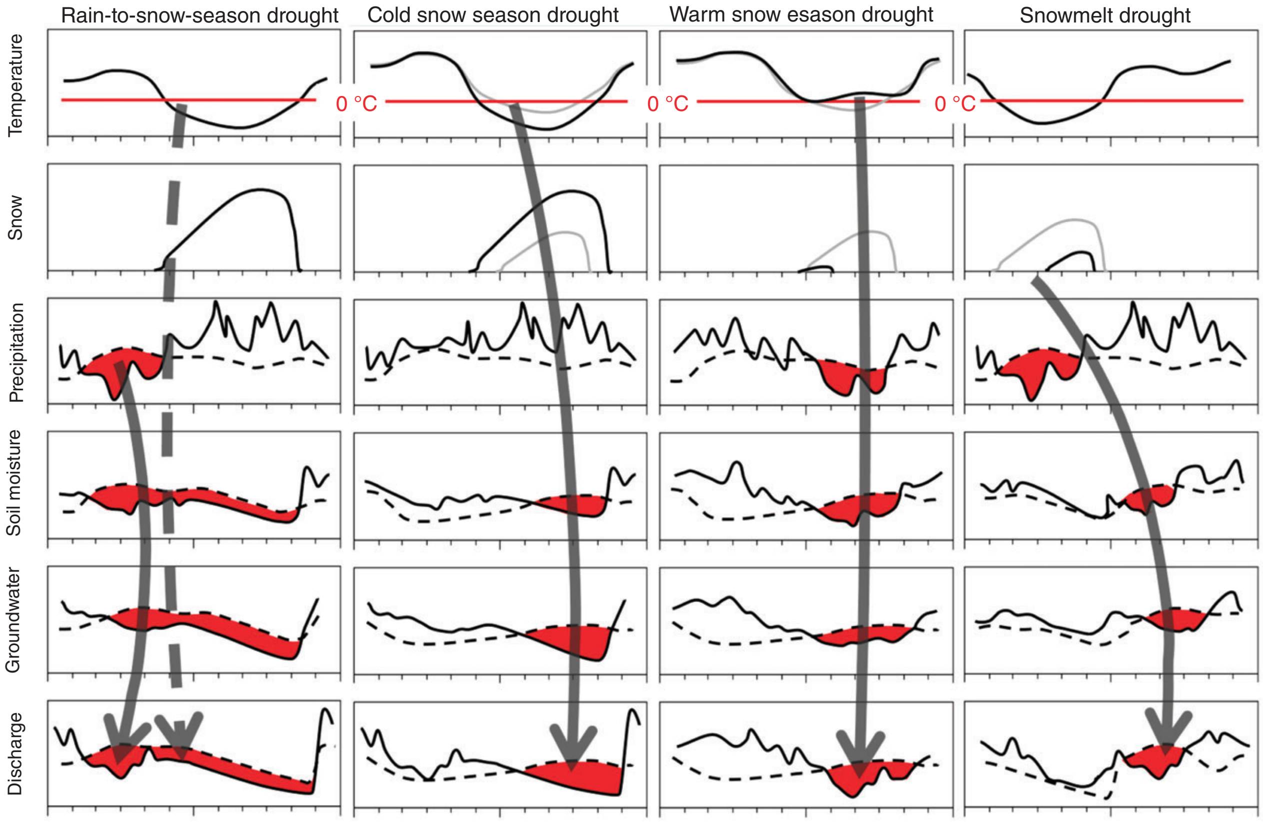

FIGURE 5 | Synthetic time series representing the propagation of a meteorological anomaly (precipitation and/or temperature) through the terrestrial hydrological cycle for a selection of hydrological drought types (Reprinted with permission from Van Loon et al.[86]). The *x*-axis represents one year and the tick marks indicate the months. The black lines are the time series of each hydrometeorological variable, the gray lines in the upper two rows are long-term averages of air temperature and snow, the dashed lines represent the threshold levels, and the red surfaces indicate drought events. Propagation of drought events is indicated by the arrows, dashed arrows represent a lack of recovery of the hydrological drought (meteorological drought ceased). For description, see Table 1

of both. Above-normal evapotranspiration was not found to be the cause of hydrological drought. Evapotranspiration can aggravate a drought event[19] and, in a dry season, can prevent recovery,[85] but it has not been found to be the sole cause of hydrological drought.

On the basis of this research, the examples in Figure 5 have been developed as alternative drought propagation graphs instead of Figure 3. Temperature-based processes are important for the development of hydrological drought just as they are for floods, as is reflected by a number of flood types that are related to air temperature, such as rain-on-snow and snowmelt floods.[138] In Merz and Bloschl,[138] two out of five flood types were (partly) governed by T control, whereas for the drought typology T control played a role in five to six out of the eight types (Table 1). And these temperature-controlled drought types also ranked higher than the precipitation-controlled drought types in the selection of the most severe drought events in the case study areas of Van Loon and Van Lanen.[85] In an application of the hydrological drought typology to global scale, Van Loon et al.[54] found that drought characteristics of hydrological drought types can be distinctly different.

Making the distinction between hydrological drought types is important for statistical analysis, attribution of change, and prediction of hydrological drought development and recovery. The different processes underlying hydrological drought development should not be confused in trend analysis[139] or climate change impact assessment.[63,140] The hydrological drought typology is a recent development based on a limited number of catchments[85,86] and modeling on the global scale.[111] It urgently needs validation in a wider range of catchments, especially to test its use in more practical applications.

Hydrological Drought Scales and Spatial Characteristics

As was mentioned previously, droughts occur on other time and spatial scales than floods. Figure 6 relates

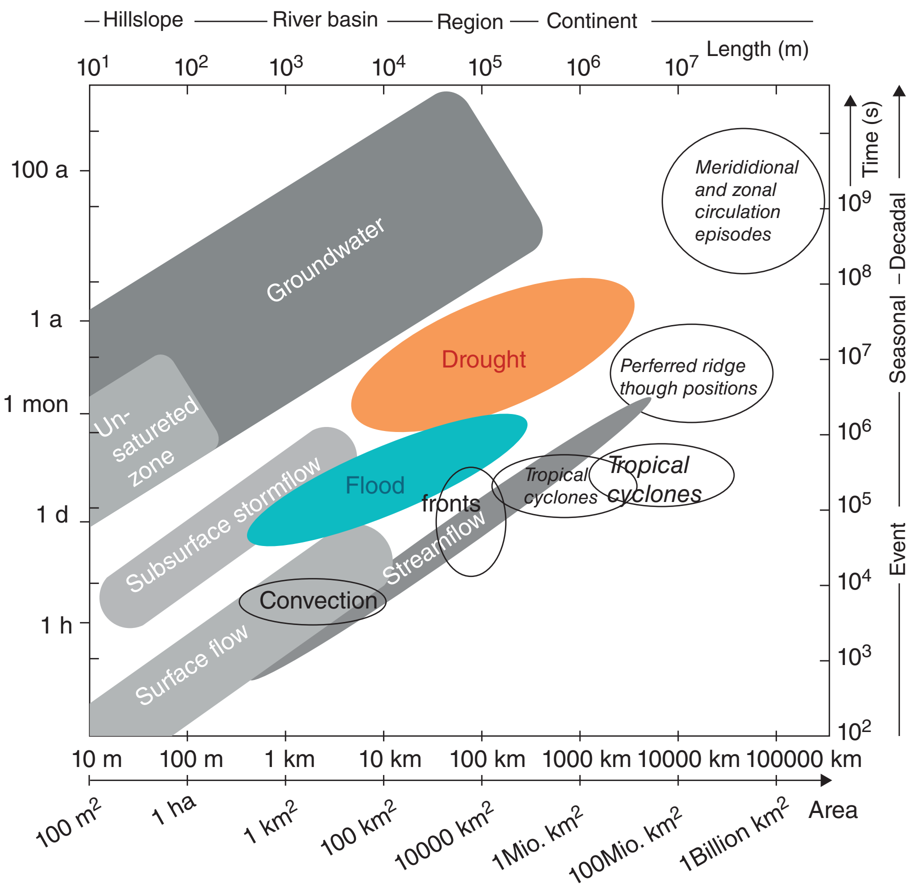

FIGURE 6 | Spatial and temporal scales of hydrological processes including floods and droughts. (Reprinted with permission from Stahl and Hisdal[66])

the scale of drought to typical scales of meteorological and hydrological phenomena see also Ref 141. Droughts typically occur on catchment to continental scales, but there are also differences in scale between meteorological and hydrological drought. Tallaksen et al.[99] found that, for a small (170 km^2) and relatively uniform catchment in the UK, meteorological droughts are short (1–2 months) and frequently cover the whole catchment, whereas hydrological droughts have a longer duration (4–5 months) and cover a smaller area. Meteorological droughts are dependent on large-scale atmospheric drivers that usually cover a large area. In contrast, the spatial pattern of hydrological drought is more patchy, because it is more dependent on local catchment characteristics and how they change the drought signal when it propagates through the terrestrial hydrological cycle. Zaidman et al.[142] found the same for the 1976 drought in Europe and concluded that there was a higher level of autocorrelation in the streamflow time series than in the precipitation time series, resulting in a lower areal coverage, but higher persistence in streamflow droughts. This was confirmed by Hannaford et al.[143] concluding that also for other events meteorological droughts in European regions were more coherent than hydrological droughts. However, large differences existed between regions and methodological differences in the calculation of indices might have influenced this conclusion.[143] In regions where convective thunderstorms are the dominant precipitation type and catchment conditions are relatively uniform, spatial drought patterns might be reversed, with more patchy meteorological droughts and spatially more coherent hydrological droughts.[141] Trambauer et al.,[144] for example, found a higher spatial variability in meteorological and soil moisture drought indices than in a groundwater drought index for a specific drought year in model results of the Limpopo basin in Africa.

Depending on the scale, different processes are dominant. For example, in large catchments elevation differences result in a large variation in precipitation and temperature over the catchment. This leads to high spatial variability, which dampens the spatial development of hydrological drought. Also the travel time within the catchment needs to be taken into account in large catchments, as it results in a different response in upstream and downstream parts of the catchment. Pandey et al.[145] found that the upper reaches of the Betwa river (43,000 km^2) in India were more prone to severe drought than the lower reaches. Trambauer et al.[144] also noted differences between the subbasins and the total basin of the Limpopo basin (415,000 km^2) in Africa. Even in a small catchment spatial variation can be important. Peters et al.,[59] for example, found that for the Pang catchment (170 km^2) in the UK short groundwater droughts are more severe near the stream and are attenuated at greater distances. Long periods of below-normal recharge have relatively more effect near the groundwater divide.

Other important spatial aspects of drought are synchronicity, clustering and breaking up of drought clusters. Most studies focused on spatial aspects of meteorological drought e.g., Refs 146, 147; there has been relatively limited research on the spatial aspects of hydrological drought. One of the first clustering methods suitable for hydrological drought is the algorithm developed by Andreadis et al.[148] for droughts in soil moisture and runoff in the USA. This clustering algorithm has subsequently been applied by Sheffield et al.[149] and Wang[150] for soil moisture drought analysis on a global scale and in China, respectively. In these studies, severity-area-duration (SAD) curves have been applied to identity severe drought events and study their characteristics and trends.[148–150] Following Andreadis et al.,[148] Vidal et al.[101] developed a clustering algorithm for meteorological and agricultural drought in France, which was applied by Vidal et al.[151] for the evaluation of the impacts of climate projections on drought characteristics. Corzo Perez et al.[152] proposed a further methodological development for the spatiotemporal characterization of hydrological drought on the global scale, allowing for runoff drought cluster evaluation at each time step. Tallaksen and Stahl[153] used the annual maximum drought cluster area as a measure of drought severity to compare large-scale model results and observations for runoff drought in Europe. They concluded that different groups of models can be distinguished based on their ability to estimate drought cluster area.[153]

Other drought studies that do not specifically use clustering algorithms, but do include a spatial dimension are Burn and DeWit,[154] Changnon,[155] Zaidman et al.,[142] Peters et al.,[59] Tallaksen et al.,[99] Santos et al.,[156] and Van Huijgevoort et al.[157]

Hydrological Drought Recovery

Research focusing specifically on hydrological drought recovery is still limited. Andreadis et al.[148] found that, using model results for the USA, droughts in runoff recover more quickly than droughts in soil moisture in response to a precipitation event. Pan et al.[158] found significant uncertainty in soil moisture drought recovery using a probabilistic framework focusing on precipitation in central USA. Van Loon and Van Lanen[85] stated that hydrological drought recovery can be hampered by snow accumulation in cold seasonal climates and by evapotranspiration in warm seasonal climates. Parry et al.[159] were the first to propose a quantitative methodology specifically aimed at characterizing hydrological drought termination. They tested the new methodology on long records of streamflow and groundwater levels for the Thames river in the UK and argue for further application of the approach to better understand the processes underlying drought termination in contrasting climates and catchment types.[159]

HYDROLOGICAL DROUGHT QUANTIFICATION

For adequate drought management, quantification of hydrological drought is essential. This includes identification of historical droughts and prediction of future droughts. In this section, I will describe commonly used drought indices, discuss data availability and modeling approaches, and give a short overview of drought prediction, historical trends, and future projections.

Drought Identification and Indices

In order to understand hydrological drought processes and impacts, drought characteristics such as the timing, duration, severity (or intensity), and spatial extent of a drought event need to be identified.[1,6,7,24,160] Their slow onset and slow recovery, the different drought categories (Figure 2) and impacted sectors (Table 1) make droughts very difficult to define quantitatively,[49] giving rise to a multitude of indices. Reviews of drought indices can be found in Heim Jr.,[161] Keyantash and Dracup,[162] Hisdal et al.,[58] Niemeyer et al.,[163] Mishra and Singh,[7] Wanders et al.,[164] Dai,[45] Sheffield and Wood,[8] Seneviratne et al.,[24] and Tsakiris et al.[77] The choice of index and its implementation are important as they can result in different conclusions, especially in the light of trends and global change.[165–168] However, there seems to be scientific consensus that there is no 'best' hydrological drought index and that a quest for the 'best' index is useless.[169] Every type of index, focusing on a specific part of the hydrological cycle or using a specific methodology, has its merit for a specific application and multiple indices should

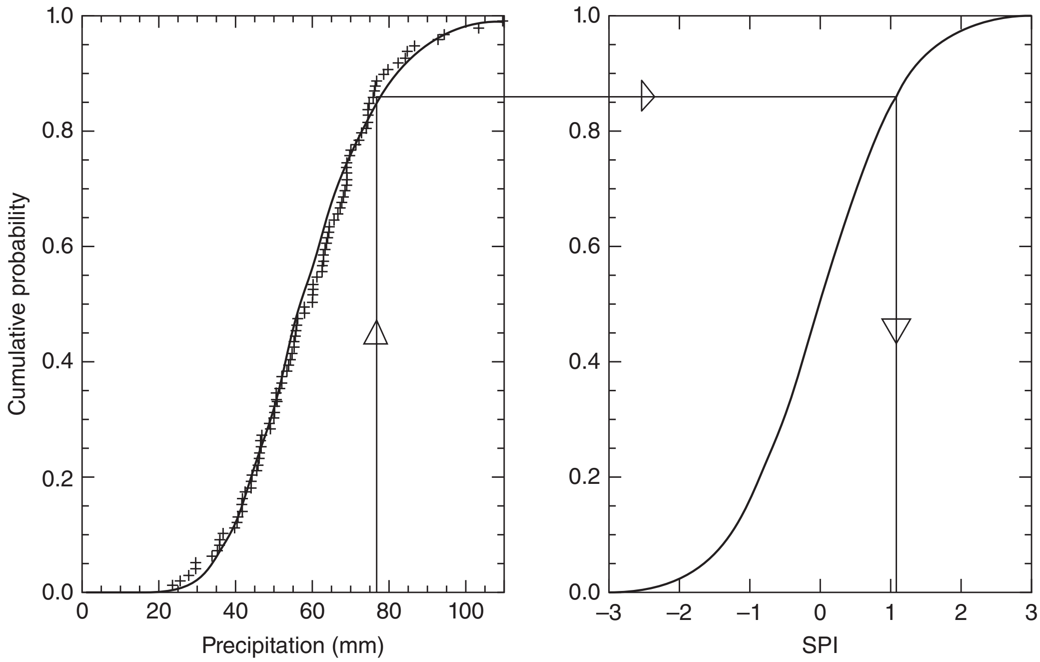

FIGURE 7 | Methodology to determine the Standardized Precipitation Index (Reprinted with permission from Lloyd-Hughes and Saunders[171]).

be used to quantify the diversity of drought impacts (Table 1).

In this section, I do not go into details on the multitude of existing drought indices. Instead I focus on a few widely used groups of indices for the characterization of hydrological drought, including some meteorological and soil moisture drought indices that are frequently used in drought propagation studies or to represent hydrological drought. Drought indices can roughly be divided into standardized indices and threshold-based indices.

Standardized Drought Indices

One group of drought indices are standardized drought indices. They have in common that they represent anomalies from a normal situation in a standardized way. The advantage is that regional comparison of drought values is possible.[7] A drawback of standardized indices is that the severity of a drought event is expressed only in relative terms, while in water resources management absolute values of the lacking amount of water with regard to 'normal' conditions (i.e., deficit volume) are needed. The set of standardized drought indices (including those focusing on hydrological drought) originate from the Standardized Precipitation Index (SPI).

SPI is the most-used standardized meteorological drought index.[170,171] It is based on long-term precipitation records that are fitted to a probability distribution (Figure 7). This distribution is then transformed to a normal distribution, ensuring zero mean and unit standard deviation. Because precipitation has a high spatial and temporal variability, meteorological drought indices often use monthly values. SPI can be computed over several time scales (e.g., 1, 3, 6, 12 months, or more) and thus indirectly considers effects of accumulating precipitation deficits.

Experts participating in a WMO drought workshop in 2009 recommended that the SPI be used by all National Meteorological and Hydrological Services (NMHSs) around the world to characterize meteorological drought.[172] Advantages of SPI are that its calculation results in normalized values and that it can be computed for different time scales.[8] Disadvantages of SPI are that only precipitation is considered, while other meteorological drivers might be important too.[45] Additionally, the length of a precipitation record and the fitted probability distribution have significant impact on the SPI values.[7,173,174] Finding the most suitable distribution can be a challenge,[101,175] especially in dry climates,[164,176] which limits the use of SPI on a global scale.

As precipitation is not the only meteorological variable influencing drought conditions, some meteorological indices also include (a proxy for) evapotranspiration. As an alternative for SPI, Vicente-Serrano et al.[177] developed the Standardized Precipitation and Evapotranspiration Index (SPEI). SPEI considers cumulated anomalies of the climatic water balance (precipitation minus potential evapotranspiration) and, like SPI, fits a probability distribution and transforms it into a normal distribution.

In snow-influenced catchments, the SPI does not always give sufficient information for drought management. To account for snowmelt explicitly, Staudinger et al.[178] introduced the Standardized Snow Melt and Rain Index (SMRI). SMRI quantifies both rain and snowmelt deficits.

Another index that reflects both precipitation and evapotranspiration and that is used in a standardized way[179] is the Palmer Drought Severity Index (PDSI). It has been developed by Palmer[180] for the USA as a tool for estimating agricultural drought damage. The PDSI is applied mainly in the USA, both for scientific and operational purposes e.g., Refs 161, 181, 182, but also increasingly on global scale e.g., Refs 165, 166, 183. It measures the departure of the moisture balance from normal conditions using a simple water balance model and can be regarded as a hydrological accounting system.[45] PDSI is sometimes classified as a meteorological drought index[45] and sometimes as a soil moisture drought index.[8] Despite its worldwide application, PDSI has important shortcomings that should limit its use on the global scale: i) the calculation procedure is complex and non-transparent,[8] ii) the time scale is fixed,[7] iii) it uses a potential evaporation method based on absolute temperature, which in some regions can have large impact,[166] iv) as it is calibrated for the USA, re-calibration is needed for application to other regions,[45] and v) snow accumulation is not accounted for and no soil moisture or vegetation control on evapotranspiration is included.[24] Palmer also developed a soil moisture drought index (Z-index) and a hydrological drought index[180] (PHDI), which have calculation procedures similar to PDSI and, therefore, the same advantages and disadvantages.

Various other standardized index for soil moisture have been proposed. For example, Orlowsky and Seneviratne[167] calculated standardized soil-moisture anomalies (SMA) by subtracting the mean and dividing by the standard deviation. Sheffield et al.[184] and Samaniego et al.[185] took a different approach for their soil moisture index and used a Beta probability distribution and kernel density estimation, respectively, to fit the data and calculate soil moisture quantiles.

Standardized indices for the characterization of hydrological drought use different hydrological variables (from observed or simulated data) as input. Most common is a focus on streamflow, because streamflow is most measured, most easily simulated, and of most interest to water resources management. Other variables used in hydrological drought indices include groundwater levels and lake levels. The Standardized Runoff Index[186] (SRI) uses simulated runoff and the Standardized Streamflow Index[187] (SSI) focuses on (observed or simulated) streamflow. Both have a calculation procedure similar to SPI, fitting a distribution to the data and transforming it to a normal distribution. Based on a similar principle, but using a nonparametric transformation instead of distribution fitting, is the Standardized Groundwater level Index (SGI), recently developed by Bloomfield and Marchant.[135] The limitations of SPI also apply to SRI/SSI and SGI, i.e., the length of the data record and the fitted distribution strongly influence SRI/SSI and SGI values.

Another issue with these (and actually all) indices is that a reference period has to be chosen, which can cause difficulties under multidecadal climate variability, like Núñez et al.[188] found for the SSI. Sensitivity of drought indices for the chosen reference period is large, similar to the sensitivity of drought trend analysis to the selection of periods.[139]

Since standardized indices with similar calculation procedures are available for all variables of the terrestrial hydrological cycle (i.e., SPI, SPEI, SMRI, SMA, SRI/SSI, SGI), they can be a useful tool in drought propagation studies, in which droughts in different compartments of the hydrological cycle are compared.[189] Standardized meteorological drought indices (based on precipitation only, e.g., SPI), calculated over long time scales are sometimes used as an approximation of hydrological drought e.g., Refs 146, 187, 190–194. In other studies this is not recommended as indices based on precipitation alone cannot capture all relevant propagation processes.[19,111,135,144,195]

Threshold Level Method

Drought characteristics can also be derived from time series of observed or simulated hydrometeorological variables using a pre-defined threshold level. When the variable is below this level, the site is in drought. Drought duration, severity, and frequency can easily be calculated. This approach is called 'threshold level method' e.g., Refs 58, 62, 196, 197, but the term 'deficit index' is also used,[65] because it measures the 'lacking' volume of water below a certain threshold (deficit volume). This is a big advantage of the threshold level method, because deficit volume is an important drought characteristic in water resources management. An example of the use of the threshold level method in water management are the calculations of drought statistical characteristics of inflows into the Júcar water resource system performed by Ochoa-Rivera et al.[198] Thresholds are, however, more often used as points for action when monitoring discharge or water volumes stored in natural and artificial reservoirs. Examples are the use of thresholds in water allocation discussions during drought in the Netherlands,[199] as reference values for discharge to inform drought management (levels: alert, alarm, and emergency) in the Po River in Italy,[200] and for reservoir management during drought in the UK.[201]

Calculation procedures for the threshold level method are elaborated in Van Loon.[54] Here, they will shortly be summarized. When one uses the threshold level method selection of a threshold level is crucial.[7] Ideally the threshold level should be related to drought impacted sectors/systems, e.g., irrigation water requirements, cooling water for industry, drinking water supply, reservoir operation levels, minimum water depth for navigation, or environmental flows to support stream ecology.[49,58,202] Often, this information is not available or the drought analysis aims at a number of sectors/systems with different requirements and, therefore, different threshold levels. Consequently, for practical reasons thresholds are often derived from percentiles of the flow duration curve, commonly ranging between the 70th and 95th percentile for perennial rivers e.g., Refs 58, 62, 99, 139, 148, 203.

Either a fixed or a variable (seasonal, monthly, or daily) threshold can be used. A variable threshold can be chosen when seasonal patterns need to be then taken into account. A variable threshold level has been used by e.g., Stahl,[55] Nyabeze,[204] Hirabayashi et al.,[205] Vidal et al.,[101] Hannaford et al.,[143] Prudhomme et al.,[206] Van Huijgevoort et al.,[157] Parry et al.,[129] Van Loon and Van Lanen,[85] Sung and Chung,[207] Van Loon et al.,[86] Prudhomme et al.[208] Beyene et al.[209] investigate how a variable threshold can best be calculated in contrasting climates. A variable threshold is most comparable to standardized indices like SPI, because for SPI a distribution is fitted for every month (or period of n months) separately (section *Standardized Drought Indices*). According to Fleig et al.,[62] there is no single threshold level that is preferable and the selection of a specific threshold level remains a subjective decision.

Each drought event can be characterized by its duration and by some measure of the severity of the event. Drought duration and severity are related, but not always linearly, as has been shown by Van Loon et al.[111] and Van Loon and Laaha.[132] For fluxes (i.e., precipitation and discharge) the most commonly used severity measure is deficit volume, calculated by summing up the differences between the actual flux and the threshold level over the drought period Hisdal et al.,[58] Fleig et al.[62] (Figure 8). This deficit

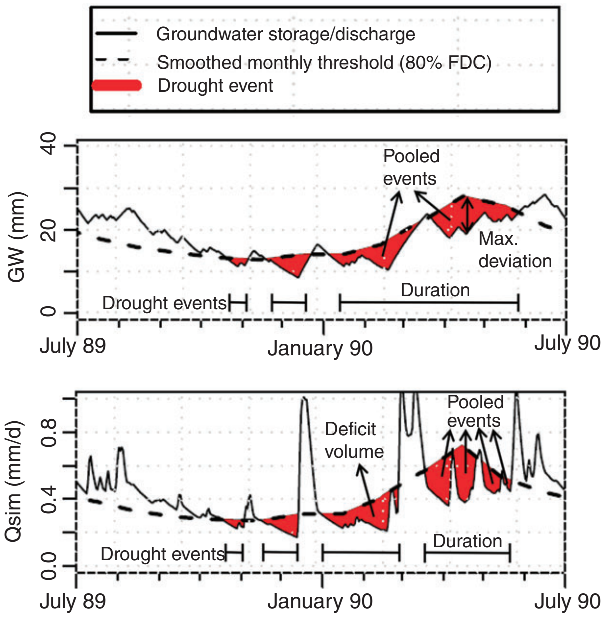

FIGURE 8 | Threshold level method with variable threshold for groundwater storage (upper row) and discharge (lower row), including an illustration of pooling method and drought characteristics duration, deficit volume, and maximum deviation.

can be standardized by dividing by the mean of the hydrometeorological variable, resulting in a variable denoting the number of days with mean flow needed to compensate for the deficit.[21,111] For state variables (i.e., soil moisture and groundwater storage) the maximum deviation from the threshold can be used as the severity measure.

Like with standardized indices, all three categories of drought (meteorological, soil moisture, and hydrological drought) can be analysed with the threshold level method. This makes comparison between variables possible, which is required when studying drought propagation. Therefore, studies on drought propagation commonly use the threshold level method e.g., Refs 53, 59, 85, 99–101, 105, 110. Another advantage of the threshold level method is that it stays as close to the original time series as possible. It does not need to fit a distribution to the data (like SPI) or use water balance computations and calibration (like PDSI).

A disadvantage of the threshold level method is that no standard drought classes are calculated, so that in global drought studies standardization is needed to prevent large differences between climate types and to enable comparison.[111] Furthermore, subjective choices cannot be avoided, for example on the threshold level to use. This is comparable to the choices of fitting a distribution when calculating standardized indices. An additional disadvantage of the threshold level method (and actually almost all drought analysis methods) for global analysis occurs in extremely dry areas with ephemeral rivers. This is due to long periods with almost no precipitation and natural zero flow, resulting in a threshold level of zero.[210] In arid climates, the use of a zero-streamflow day or zero-streamflow month approach (comparable to the Consecutive Dry Days method, or CDD, which counts the number of consecutive days with precipitation less than 1 mm[211]) is more appropriate than the threshold level method. Van Huijgevoort et al.[212] therefore developed a new method for the characterization of streamflow drought on large scales based on a combination of the threshold level method and the CDD method. In other global scale studies arid regions are removed from the analysis e.g., Refs 152, 208.

Recent Developments in Drought Indices

Besides at-site indices, some regional indices exist that quantify the spatial aspect of drought e.g., Refs 59, 99, 148, 149. Most of these indices calculate the portion or percentage of an area in drought. The Regional Deficiency Index (RDI), for example, divides the number of catchments in drought by the total number of catchments[143,55] and the Regional Drought Area Index (RDAI) divides the drought area by the total area of the region.[82]

For hydrological drought characterization often composite drought indices are recommended.[169] These should incorporate 'streamflow, precipitation, reservoir levels, snowpack, and groundwater levels'.[169] The European Drought Observatory (EDO), for example, uses a Combined Drought Indicator[213] (CDI). EDO provides 10-day updates of the agricultural drought status in Europe by integrating the meteorological index SPI (on 1, 3, and 12-month scales), simulated soil moisture anomalies, and a vegetation stress indicator derived from satellite information. Currently, no hydrological drought information is incorporated in the CDI of the European Drought Observatory yet. In contrast, the US Drought Monitor uses streamflow percentiles and other hydrological indices to come to drought intensity categories (www.droughtmonitor.unl.edu/AboutUs/ClassificationScheme.aspx).

Like CDI, some newly developed drought indices are derived from or incorporate satellite information. Advantages are that satellite data provide a large spatial coverage and high spatial resolution (see section *The Use of Observational Data in Hydrological Drought Quantification*). Most of them, however, focus on soil moisture and vegetation.[214,215]

The Use of Observational Data in Hydrological Drought Quantification

For the calculation of drought indices, availability of long time series of undisturbed, good-quality observational data is essential.[216,217] It is beyond the scope of this paper to discuss all data sources that are or can be used in hydrological drought research. Currently, the best description of observational data with a focus on low flow and drought is Rees et al.[217] Here, I give an overview of some recent developments and approaches to deal with uncertainty and ungauged catchments.

Observational data sources used in drought studies are either station data (e.g., meteorological stations, discharge gauging stations, groundwater wells) or gridded data (e.g., reanalysis data, satellite data). In hydrological drought studies, most commonly used data are streamflow measurements. Large-scale river flow archives,[218] like the Global Runoff Data Centre (GRDC) and the European Water Archive (EWA), collect and store discharge datasets from stations around the world and in Europe, respectively. These archives are important for low-flow trend studies,[219] comparative streamflow drought studies,[129] and validation of low-flow simulations.[63,140,220] For water balance studies,[19] the network of FLUXNET data[221] is useful. Unfortunately, no large-scale data archive exists for timeseries of groundwater levels. The recently started Global Groundwater Monitoring Network (GGMN) initiative of the International Groundwater Resources Assessment Centre (IGRAC) might fill this gap.

Despite the availability of some large-scale datasets, there is limited use of hydrological data in large-scale drought monitoring systems.[23,143] The drought monitor of the European Drought Observatory (EDO) is based on precipitation measurements, modeled soil moisture, and remotely sensed vegetation state. The US Drought Monitor does include streamflow percentiles in its composite drought categories, but is dominated by meteorological and soil moisture drought information.

Although there are indications that satellite products using vegetation, evaporation, and soil moisture relate to streamflow drought,[222] the use of satellite data focusing on hydrological drought monitoring is still limited. One satellite product that can be applied in hydrological drought monitoring is NASA's Gravity Recovery and Climate Experiment[223,224] (GRACE). The GRACE satellite measures total terrestrial water storage on a 300–400 km resolution at monthly intervals and drought indices based on GRACE data have been proposed by Houborg et al.[225] and Thomas et al.[226] The US Drought Monitor offers

GRACE-based drought information as an experimental product (www.drought.unl.edu/MonitoringTools/NASAGRACEDataAssimilation.aspx). One of the issues that currently limits the use of datasets like GRACE is their coarse resolution compared with the requirements of local water management. Assimilation of GRACE data into a high-resolution model is needed to overcome this scale gap.[194]

All observational data has uncertainty. In general, discharge measurements are more uncertain in the low-flow range than for average flow conditions.[217] This is important to take into account in streamflow drought analysis. Lack of available data is generally a problem in water management, but especially in drought management. The International Association of Hydrological Sciences (IAHS) recently concluded a decade on Prediction in Ungauged Basins (PUB), which boosted research on this topic. Results of this decade are summarized in Blöschl et al.[227] In the chapter on drought and low flows, Laaha et al.[65] give an overview of regionalization methods used for transferring information about drought and low flow to ungauged basins and their results in a number of case studies.[228]

Hydrological Drought Modeling

Often observational records are not long enough, some variables are not monitored at all, data quality is too low, or observations are influenced by human activities. To overcome these problems hydrological models can be used to extend data series, fill gaps, and naturalize disturbed time series.[1,7,8,24,45] Modeling is current practice in hydrology, both in science and in operational water management. Hydrological models range from simple statistical models with a few parameters via conceptual models with varying complexity to complex physically based models (for an overview of current hydrological modeling approaches, see for example Wagener et al.,[229] Matonse and Kroll,[230] Beven,[231] and for an overview of drought modeling approaches, see for example Wagener et al.,[229] Matonse and Kroll,[230] Beven,[231] and for an overview of drought modeling approaches, see Mishra and Singh[232]). For drought management, which is primarily on catchment scale, conceptual rainfall-runoff models are the main tool.

Hydrological models are usually designed to simulate average and high flows and have been shown to give good results in catchments around the world. Unfortunately, low flows are often not captured satisfactorily by models.[124,233–238] Simulating low flows is a challenge. Smakhtin[61] describes a number of difficulties in the modeling of low flows and Staudinger et al.[239] state that 'low flows are often poorly reproduced by commonly used hydrological models, which are traditionally designed to meet peak flow situations'.

Recently, various attempts have been made to improve low-flow modeling using existing models. Perrin et al.[240] improved a lumped rainfall-runoff model to match both high and low flows. Matonse and Kroll[230] used hillslope storage models (i.e., kinematic wave hillslope storage and hillslope storage Boussinesq models) to improve groundwater flow in a small steep headwater catchment. Romanowicz[241] used a combination of a physically based model (TOPMODEL) and stochastic transfer functions based on a logarithmic transformation of flows. Basu et al.[237] focused on riparian zones to improve low-flow modeling in a simple threshold-based model. Pushpalatha et al.[242] added a routing reservoir to a conceptual rainfall-runoff model. These studies show some improvement in the simulation of low flows, but no approach is explicitly the best.

The basic drought propagation processes, e.g., fewer and longer events moving from meteorological drought via soil moisture drought to hydrological drought, an attenuated deficit in hydrological drought compared with meteorological drought, as well as differences between catchments with contrasting climate and catchment characteristics, are generally reproduced by different model types, such as catchment-scale conceptual models,[85,101] an ensemble of large-scale physically based models,[243] and a synthetic model.[110] The large diversity of the processes underlying drought propagation (e.g., related to temperature and storage; section *Drought Propagation*), however, is not always reproduced well by all model approaches. Gudmundsson et al.,[244] Stahl et al.,[245] Van Loon et al.,[243] Van Huijgevoort et al.,[157] and Tallaksen and Stahl[153] tested a number of physically based, distributed, large-scale hydrological models and land surface models from WaterMIP[246] (Water Model Intercomparison Project) on their suitability to reproduce hydrological drought. The conclusions from these studies were that: (1) there are large differences in hydrological drought simulation between the models, (2) the ensemble mean/median is better than any of the individual models, (3) the models' representation of snow and groundwater storage and release processes is problematic since it leads to a lack of persistence. This is in agreement with Dadson et al.,[247] who evaluated the role of land surface models for water management decisions under global change.

Just like observational data, model outcomes contain uncertainties. Uncertainty in hydrological model results originates from input data uncertainty,[248] calibration data uncertainty,[249] and model uncertainty.[250] Model uncertainty can be subdivided in structural uncertainty (i.e., related to model structure), parametric uncertainty (i.e., related to model parameters and their identification), and numeric uncertainty[251] (i.e., related to numerical techniques). There is little knowledge of the relative importance of these different sources of uncertainty during low flow and drought, since most studies have focused on average and high flows e.g., Refs 248, 249.

Due to the multitude of sources of uncertainty described above, the quantification of hydrological drought might be regarded as much more uncertain than the quantification of meteorological drought. In contrast, the high temporal variation in precipitation might result in erratic behavior that is apparent in meteorological drought and is filtered out in hydrological drought. This is related to the different scales mentioned previously (section *Hydrological Drought Scales and Spatial Characteristics*). As hydrological droughts generally occur on larger time scales than meteorological droughts, whereby the terrestrial hydrological cycle acts as a low-pass filter of the highly variable meteorological inputs, errors in the meteorological forcing are filtered out. This is especially true during dry conditions (more than during floods) because the relative contribution of slow pathways in a catchment to discharge is higher during drought.

Forecasting Hydrological Drought

In operational water management forecasts are important. Knowledge about drought propagation is imperative to various areas of prediction of hydrological drought. Recent developments in drought prediction and forecasting are described in Pozzi et al.[23] The authors explore the need for a global drought early warning system and argue that current challenges are: 'a lack of in situ measurement networks, modest seasonal forecast skill in many regions, and the lack of infrastructure to translate data into useable information'. Pozzi et al.[23] also explicitly mention the diversity of variables that need to be monitored to capture the development of hydrological drought and its impact on different water-related sectors.

Improvement of the seasonal forecasting of hydrological drought is a prerequisite for adequate operational water management (e.g., reservoir operation, irrigation abstractions, or management of wetlands). Most of the recent developments in drought forecasting, however, focus on meteorological drought e.g., Refs 252, 253. Some seasonal forecasting of soil moisture is done for agricultural drought in recent studies e.g., Refs 254, 255, but forecasting of hydrological drought variables is still limited.[23] Luo and Wood[256] focus on seasonal forecasting of hydrological variables using seasonal climate forecasts from an ensemble of climate models and a hydrological model in the Ohio River basin. Fundel et al.[257] use a combination of weather forecast and a hydrological model to predict streamflow drought in the Swiss pre-alpine region. Demirel et al.[258] quantify appropriate lags and temporal resolution for the prediction of low flow indicators in the Rhine River and Demirel et al.[259] found that for the Moselle River models tend to over-predict runoff during low-flow periods and they are more sensitive to ensemble precipitation forecasts than to ensemble PET forecasts. Trambauer et al.[260] review hydrological models for hydrological drought forecasting in Africa.

Another approach is to predict 'drought from drought', meaning the prediction of hydrological drought from meteorological drought.[143] Hannaford et al.[143] attempt to predict hydrological drought for the UK based on meteorological drought indicators of the target region and hydrological drought indicators of other regions in Europe. Wong et al.[261] similarly apply drought propagation knowledge in predicting hydrological drought from preceding meteorological droughts using statistical methods in contrasting catchments in Europe.

Other studies explore the use of the correlation between hydrological drought indices and large-scale ocean-atmospheric modes (like ENSO) for forecasting of hydrological drought e.g., Refs 87, 144, 262, 263, but many conclude that the link is 'not sufficiently strong to consistently predict streamflow accurately'.[23,264] More research on this issue is needed before hydrological drought forecasting can be successfully applied in operational water management. Special focus is needed on the recovery of hydrological drought during an ongoing event.

Trends and Projections for the Future

Some of the pressing questions are: have droughts become more frequent or severe in recent decades? And: will they become more frequent or severe in the future? Several studies investigated trends in drought occurrence, both on global and on regional scales e.g., Refs 24, 139, 265, but most focused on meteorological and soil moisture drought. On a global scale, for example, different studies on meteorological drought trends yield conflicting results. Dai[45] found increasing drought using PDSI (see section *Standardized Drought Indices*), whereas Sheffield et al.[166] did not find a trend in global drought using the same drought index, but different data and methodology. Overall, there are still large uncertainties regarding observed global-scale trends in meteorological drought[24] and the applied methodology has a large influence on the magnitude and sometimes also on the sign of observed trends.[166]

Seneviratne et al.[24] summarize the regional-scale studies as follows: 'there is medium confidence that since the 1950s some regions of the world have experienced trends toward more intense and longer droughts, in particular in southern Europe and West Africa, but in some regions droughts have become less frequent, less intense, or shorter, for example, central North America and northwestern Australia'. For Europe, Lloyd-Hughes and Saunders[171] found no significant trends in the area under extreme and/or moderate drought according to SPI and PDSI. However, when focusing on the Mediterranean, Sousa et al.[266] did find significant drying trends in PDSI. Stahl et al.[219,245] found a coherent picture of annual streamflow trends in both observations and multi-model ensemble results, with negative trends (lower streamflow) in southern and eastern regions and generally positive trends (higher streamflow) in western and northern regions. Additionally, a decrease in summer low flows was observed in large parts of Europe, including many regions in western Europe.[245] Trends in hydrological drought have only been studied by Hisdal et al.[139] In their analysis of streamflow drought severity and frequency in Europe over the period 1962–1990, no significant changes were detected for most stations. They did find trends toward increasing drought deficit volume in Spain, eastern Europe, and the UK, and decreasing drought deficit volume in central Europe, but could not conclude that drought conditions in general have become more severe or frequent.[139]

There is some consistency in model projections for the future suggesting a dryer and warmer Mediterranean region and a northward shift of climatic regimes in Europe e.g., Refs 267–272. As a result there will be an enhancement of interannual variability in the European summer climate, associated with higher risks of heat waves and droughts e.g., Refs 24, 63, 71, 235, 270, 273. In many regions around the world, there is less confidence about future drought occurrence due to larger uncertainties in model projections.[24,270]

Recent studies on future hydrological drought include Vidal et al.,[151] Orlowsky and Seneviratne,[167] Forzieri et al.,[274] Prudhomme et al.,[208] Van Huijgevoort et al.,[140] Törnros and Menzel,[275] and Wanders et al.[195] In these studies the topics of choosing suitable hydrological models, reducing the uncertainty, and selection of appropriate indices and quantification methods for the future are treated. Orlowsky and Seneviratne[167] found that, for the near future, internal climate variability is the dominant source of uncertainty in projections of soil moisture drought and for the far future (end of the 21th century) the differences between climate models become dominant. Prudhomme et al.[208] found similarly high uncertainties in projections of streamflow drought due to the different representations of terrestrial water-cycle processes in hydrological models. Van Huijgevoort et al.,[140] therefore, propose to reduce uncertainty in streamflow drought projections by selecting climate model—hydrological model combinations that performed best in the control period. Van Huijgevoort et al.[140] used the threshold level method, but noticed that regime changes in snow-dominated catchments can lead to unexpected increases in drought severity. The unwanted influence of regime changes on drought characteristics can be overcome by using a transient reference period for the calculation of the drought index. Wanders et al.[195] applied a transient threshold level into the future based on the assumption that society and the environment adapt to changing drought conditions. Vidal et al.[151] used a similar approach but distinguished between 'retrospective adaptation' and 'prospective adaptation'. Both concluded that adaptation reduces the expected changes in drought severity. In a global-scale model comparison study, Prudhomme et al.[208] noted the strong influence of including the adaptation of plants to increased levels of CO_2 in a hydrological model. In contrast to other models, that particular model predicted little or no increase in streamflow drought frequency for the future.[208]

Despite the uncertainties and the debates about the best methodology for studying droughts in the future, there are hotspots where models and approaches agree on the projected changes in hydrological drought. Hotspots of more frequent drought are projected in South Africa and Central America[167] and hotspots of increased drought severity in o.a. the Middle East, the south-eastern United States, Chile, and south-western Australia.[208]

Other, more qualitative approaches use drought propagation knowledge for estimates of hydrological drought occurrence in the future. Knowledge of climate and catchment control on drought propagation processes can assist in the assessment of the effect of global change on drought patterns. For example, a shift in climate leads to a shift in the occurrence of hydrological drought types.[85] This might be important in regions where winter droughts change from drought types that always end with a snow melt peak to drought types that continue into the summer.

HYDROLOGICAL DROUGHT IMPACTS AND MANAGEMENT

Predictions and future projections of hydrological drought are of little use when the link to the impacts of drought on the ecosystem and society (Figure 1) is not clear. Research on the relation between the physical hazard of hydrological drought and its impacts is still in its infancy. Information on drought impacts is now being collected by the Drought Impact Reporter (DIR) of the National Drought Mitigation Center (NDMC) in the USA, by the European Drought Observatory (EDO) of the Joint Research Centre (JRC), and by the European Drought Impact report Inventory (EDII) of the DROUGHT-R&SPI project in Europe. These relatively new data sources are now starting to be explored.[86,276–280]

Estimates of drought impacts in recent years indicate that drought-related losses are increasing.[12] It is difficult to isolate the impacts of climate change from changes in, for example, land use and increasing vulnerability.[77] Important factors for increased vulnerability are population growth, concentration of people in urban areas and semiarid regions, globalization of food markets, and water accessibility issues. Impacts of drought are likely to increase with time as society's demands on water and environmental services increase.[281] Conflicts between water users have emerged. Worldwide drought has been a stressor for international relations in transboundary rivers[282,283] and is expected to continue to be so in the future.[284] Although droughts occur everywhere, it is important to note that, in general, the most severe consequences of drought for humans occur in arid or semiarid regions where the availability of water is already low under normal conditions, the demand often is close to or even exceeds the natural availability and society often lacks the ability to adapt to the drought hazard.[45] Therefore, drought management is and will increasingly be crucial.

In the European Union, the Water Framework Directive demands member states to preserve or recover a 'good status' in all water bodies[285] and member states are encouraged to implement drought management measures in River Basin Management Plans.[286] River basin management, which in many places needs to balance between the two hydrological extremes flood and drought, needs information and tools to take both extremes into account equally. All around the world programs exist to save water, to rely more on desalinated water, rainwater harvesting, wastewater reuse, or water transfer,[286–290] some of which are quite controversial. The main issue is moving from short-term crisis management to long-term planning including pro-active measures.[6]

CHALLENGES FOR HYDROLOGICAL DROUGHT RESEARCH

On the basis of the state-of-the-art of hydrological drought research presented in this paper and the current discussion in the scientific community, a number of research gaps and challenges can be defined:

1. Further our understanding of hydrological drought;
2. Better quantification of hydrological drought;
3. Moving to including the human aspects of hydrological drought;
4. Application of drought research in water management and policy.

In this section these challenges will shortly be discussed.

Challenge 1: Further Our Understanding of Hydrological Drought

For long-term hydrological drought planning and management, increased knowledge of the physical processes governing hydrological drought is needed so that forecasting, early warning, and the link with the impacts of drought are improved. There are still some issues in the hydrological processes underlying drought propagation that remain to be understood, especially in relation to catchment control. How is a catchment modifying climate input through storage and release processes? How does this effect relate to catchment characteristics? How is it changing spatially and temporally? What is the role of evapotranspiration? These questions still need to be answered.

According to scientists in the fields of large-scale drought monitoring and forecasting, the terrestrial processes of drought development require more attention.[7,22,23] In the recent IPCC report on extremes, Seneviratne et al.[24] write:

The space–time development of hydrological drought as a response to a meteorological drought and the associated soil moisture drought (drought propagation e.g., Ref 53) needs more attention. There is some understanding of these issues on the catchment scale e.g., Ref 99, but these need to be extended to the regional and continental scales. This would lead to better understanding of the projections of hydrological droughts, which would contribute to a better identification and attribution of droughts and help to improve global hydrological models and land surface models.

Especially the spatial aspects of hydrological drought and processes underlying the termination of hydrological drought events deserve more attention in research.[232] Hydrological drought recovery is crucial in water resources management. As drought is a 'creeping disaster' it is often only noticed when it is already well developed and at that stage the single most important question in water management is: when will it end?

Challenge 2: Better Quantification of Hydrological Drought

In drought management indices are often used because they reduce a complex problem to a single number. However, water managers should be very careful in choosing indicators. The Standardized Precipitation Index (SPI) has an increasing popularity, because it is relatively easy to apply, precipitation data are usually available, and results are given in classes ranging from moderate drought to exceptional drought. These are good characteristics for indicators to be used on large scales and for the general public (they are sometimes called 'awareness' indicators), but in local water resources management often more specific information is needed. It should be noted that many processes are not incorporated in indices that use only precipitation or precipitation and temperature. Teuling et al.[19], for example, stress 'the need for a correct representation of evapotranspiration and runoff processes in drought indices' and Staudinger et al.[178] argue for incorporating snow processes into drought indices. Since there is no single 'best' hydrological drought indicator, the question of how to use a multitude of drought indices or even a composite index in hydrological drought monitoring is still to be investigated.[169]

Large-scale data collection and consolidation initiatives, including satellite data like GRACE e.g., Refs 291, 292, and large-scale river flow archives,[218] provide a wealth of observational data on larger scales, of which the potential for drought research should be explored more intensely. Continued measurement of hydrometeorological variables is important for quantification and modeling of hydrological drought, because models need to be forced with observed meteorological data and hydrological data are needed for calibration and validation. In the fields of hydrological drought modeling, forecasting, and projections for the future, advances are being made, but more research is needed to improve.[160,293] For future hydrological drought studies, the questions of which model or model ensemble, which indices, and which methodology to use is still topic of debate.[140,151,195,208]

Challenge 3: Moving to Including the Human Aspects of Hydrological Drought

This paper focused on physical processes related to drought, not on societal aspects. Anthropogenic effects are, however, sometimes hard to neglect because they affect observed hydrometeorological variables. Anthropogenic effects on the water cycle related to drought can be direct and indirect. Direct effects are decreases of water availability by e.g., abstractions from surface water or groundwater, water diversions, and construction of reservoirs. Indirect effects are related to changes in the hydrometeorological system, leading to a decrease in water availability. For example, changes in land use can result in a faster runoff to the stream and, therefore, to lower groundwater levels. Global warming can lead to increased evapotranspiration or changes in the precipitation pattern, resulting in lower streamflow.

Recently, Sivapalan et al.[48] introduced the concept of 'socio-hydrology', a new science of people and water. The focus of socio-hydrology should be on 'observing, understanding and predicting future trajectories of co-evolution of coupled human-water systems'.[48] The link between hydrological drought and society is a new field of research that is highlighted by the International Association of Hydrological Sciences (IAHS) in their new scientific decade on Change in Hydrology and Society called 'Panta Rhei'.[294] Analyses of the relation between the physical causes and dimensions of drought and its impacts are a promising way forward, as was shown in Stahl et al.,[12] Van Loon et al.,[86] and O'Brien et al.[295] Other recent studies looked at the other side of the spectrum, namely human influences as additional driver of drought.[220,296]

Adding the human dimension to drought research could be the right way to bridge the gap between the social and the natural sciences,[48] as is also advocated for floods by Di Baldassarre et al.[297] Vincent[298] states that the interplay of nature-technology-society is important both in the light of generating knowledge and awareness, and in order to resolve conflicts that may arise in situations of water scarcity.[299]

Challenge 4: Application of Drought Research in Water Management and Policy

One step further is bridging the gap between science (both natural and social) and management and policy.[300] Quevauviller et al.[285] put forward arguments for the strengthening of the links between the scientific and the policy-making communities by discussing the implementation of the EU Water Framework Directive[301] with a wide range of experts and stakeholders. Quevauviller et al.[285] see the interaction between science and policy as a two-way process on different levels (EU, national, and regional) that requires a constant dialog and a mediator mechanism to come to optimal results. Batubara et al.[302] argue that a stronger interface between policy makers and scientists in the EU is necessary to ensure that research better addresses specific requests of the EU's Groundwater Directive. In other regions around the world similar initiatives are needed to apply recent scientific finding in drought management and policy.

CONCLUDING REMARKS

Hydrological drought is complex in terms of its causing factors and impacts on ecosystems and society. It is a challenge to the scientific community to help elucidate the phenomenon. In this review, the topics of drought definition, drought processes, and drought quantification have been treated extensively. Nevertheless, this review does not pretend to be complete. The most important objectives were to give a broad overview of the topic of hydrological drought and to provide advice for further reading on specific topics within that. This could be of use to scientists in other fields of study who are interested in drought, for water managers who have to include drought in river basin management plans and want to get a grip on the issue, for teachers and students at universities and high schools who want to teach/learn about drought issues. Hopefully, this will then contribute to a further understanding of hydrological drought in general, so that the adverse impacts of drought mentioned in section *Hydrological Drought in Context* could be prevented or alleviated in the future.

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